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# PRELIMINARY INVESTIGATION OF A STICK SHAKER AS A LIFT-MARGIN INDICATOR

A Thesis

Presented to

the Faculty of the Department of Engineering

University of Virginia



In Partial Fulfillment

of the Requirements for the Degree

Master of Aeronautical Engineering

by

James P. Trant, Jr.

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APPROVAL SHEET

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Aeronautical Engineering

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TABLE OF CONTENTS


| CHAPTER | | PAGE |
|---|---|---|
| I. | STATEMENT OF THE PROBLEM . . . . . . . . . . . . . . | 1 |
| II. | REVIEW OF THE LITERATURE . . . . . . . . . . . . . | 5 |
| III. | APPARATUS . . . . . . . . . . . . . . . . . . . . | 9 |
| IV. | PROCEDURE AND RESULTS . . . . . . . . . . . . . . | 18 |
| | Ability of Subject to Maintain a Selected Stick-Shaker Frequency and Amplitude . . . . | 18 |
| | Description of tests . . . . . . . . . . . . | 18 |
| | Results. . . . . . . . . . . . . . . . . . . . | 21 |
| | Ability of Subject to Detect Changes in Frequency or Amplitude . . . . . . . . . . . | 26 |
| | Description of tests . . . . . . . . . . . . | 26 |
| | Results. . . . . . . . . . . . . . . . . . . . | 28 |
| V. | RECOMMENDATIONS FOR FURTHER RESEARCH . . . . . . | 33 |
| VI. | CONCLUDING REMARKS . . . . . . . . . . . . . . . . | 40 |
| BIBLIOGRAPHY . . . . . . . . . . . . . . . . . . . . . . | | 42 |
| APPENDIX . . . . . . . . . . . . . . . . . . . . . . . . | | 45 |

LIST OF FIGURES


| FIGURE | | PAGE |
| --- | --- | --- |
| 1. | Photograph of Stick Shaker . . . . . . . . . . . . . | 10 |
| 2. | Frequency-Response Calibration of Stick and Shaker Combination for Shaker With Rubber Buffers. Lines Fairing the Data Points are for Constant Pressure. Typical Wave Forms are Shown at Indicated Points . . . . . . . . . . | 11 |
| 3. | Schematic Diagram of the Arrangement for Imposing an Arbitrary Input of Frequency and Amplitude of Stick Vibration, for Allowing the Subject to Compensate for the Arbitrary Input, and for Measuring the Subject's Performance . . . . . . | 14 |
| 4. | Photograph of Stick-Shaker Equipment With Subject Ready for Test . . . . . . . . . . . . . . . . . | 15 |
| 5. | Block Diagram Illustrating the Ideal Functional Characteristics of the Apparatus in Tests to Determine Ability of a Subject to Maintain a Selected Stick-Shaker Frequency and Amplitude. . | 16 |
| 6. | Variations of Frequency and Double Amplitude of Stick-Shaker Vibration With Switching or Output Cam Displacement (in Step Numbers) Used in Tests to Determine Ability of Subject to Maintain a Selected Stick-Shaker Frequency and Amplitude. . | 19 |

FIGURE PAGE

7. Time Histories of Disturbance Input and Subject Output in Terms of Equivalent Stick Displacement Showing Ability of Subject to Maintain a Selected Stick-Shaker Frequency and Amplitude . . . . . . 22

8. Frequency Distribution of the Ratio of Change in Amplitude of Stick Vibration Detected to the Basic Amplitude . . . . . . . . . . . . . . . . 29

9. Frequency Distribution of the Ratio of Change in Frequency of Stick Vibration Detected to the Basic Frequency . . . . . . . . . . . . . . . . 30

10. Limits of Stick-Shaker Vibration Estimated Usable in Aircraft (Cross-Hatched Area). Also Shown are Symbols and Outlines (Dashed Lines) Representing the Present Tests and Variation C Suggested for Use in Aircraft if Resolution Equivalent to 11 Stages was Required . . . . . . . 35

## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | basic double amplitude, inches |
| $A_1$ | minimum basic double amplitude, inches |
| $A_n$ | maximum basic double amplitude, inches |
| $\Delta A$ | change in double amplitude, inches |
| $f$ | basic frequency, cps |
| $f_1$ | minimum basic frequency, cps |
| $f_n$ | maximum basic frequency, cps |
| $\Delta f$ | change in frequency, cps |
| $K$ | constant |
| $n_A$ | maximum number of steps or stages of amplitude obtained within given amplitude limits |
| $n_f$ | maximum number of steps or stages of frequency obtained within given frequency limits |

# CHAPTER I

## STATEMENT OF THE PROBLEM

In order to obtain the shortest possible landing run or the lowest possible carrier arresting gear loads for a given airplane with a specified loading, it is necessary to land at the minimum energy condition. The minimum energy condition should occur at the stalling speed but, in the approach to a landing, a practical minimum must be accepted at a speed slightly higher than but as near to stall as possible to avoid inadvertant stalling due to air turbulence, to allow for flight path adjustment and flaring, and to allow time for engine acceleration in case of waveoff. It is also necessary to maintain an even greater speed margin above stall in the approach to a landing in many modern high performance airplanes because the design features necessary to obtain many of the satisfactory stalling characteristics have often been sacrificed or compromised because they were incompatible with the design features necessary to obtain the high performance such as sweepback and thin uncambered wings. One of the satisfactory stalling characteristics often sacrificed is adequate stall warning. In many airplanes adequate stall warning occurs naturally as a consequence of the aerodynamic conditions associated with the onset of the stall; in others it may be obtained with instrumentation designed for the purpose. It has been suggested that the instrumentation used for stall warning be modified so as to combine with its normal function the function of indicating the margin of lift coefficient below stall or correspondingly the margin of airspeed above stall. The combined instrumentation would then aid the pilot in obtaining as near as possible a minimum energy landing and in avoiding stalling in the approach.

Instrumentation used for stall warning generally consists of a detector, an indicator, and a connecting link. Most detectors and the connecting links require little or no modification to make them capable of presenting to the indicator signals which may be used for indicating lift margin as well as stall warning. The indicator used for stall warning is usually a control stick shaker. Alloting stall warning to the sensation of the control stick vibration through the hand increases the use of the channels of the nervous system available, and thus does not impose an additional burden on the other senses which are already engaged in their normal duties. Furthermore, the stick shaker is known to be acceptable to pilots probably for the above reason.

When the stick shaker is used as a lift-margin indicator it is necessary to change the frequency or amplitude of vibrations with the lift margin. Some work has been done in the industry toward using the stick shaker as a landing-approach-condition indicator as well as a stall-warning indicator by providing two stages of stick vibration of different frequencies and amplitudes, one actuated at the angle of attack or lift coefficient desired for the landing approach and the other actuated at the prescribed stall-warning margin. This arrangement does not, however, appear to be entirely satisfactory because it would supply no indication of the magnitude of variations from the desired flight condition, which would therefore be difficult to maintain. The question has arisen as to whether a desired lift coefficient or angle of attack could be maintained by the pilot with sufficient accuracy to eventually allow a safe reduction of the lift margin below the stall if he were provided with a continuous angle-of-attack or lift-coefficient detector which would supply a continuous variation of either stick-shaker frequency or amplitude, or both, over the desired range of lift coefficient.

In order to provide some information on this question, two types of tests were devised using ground simulator equipment in the laboratory simulating a stick-shaker installation in an airplane. In one type, a number of subjects were tested to determine how well they could maintain a given stick-shaker frequency and amplitude by movement of the control stick in an effort to compensate for an imposed arbitrary change in stick-shaker frequency and amplitude simulating, for example, a change such as might be associated with a change in lift margin in flight. For these preliminary tests, a large number of discrete changes in frequency and amplitude with change in stick position were used instead of a continuous variation which could not be obtained with the available equipment. The other type of test was made to determine the average minimum change in stick-shaker frequency and amplitude that a subject could detect. All of the tests were made within an amplitude range from about 0.006 to 0.3 inch (measured near the top of the stick) and a frequency range from about 4 to 26 cycles per second.

## CHAPTER II

## REVIEW OF THE LITERATURE

A few of the many papers on stalling (and stall warning) and on various types of detection devices are mentioned since they supply background information to the problems concerned with indication of warning to the pilot.

Both Gilruth[1] and Phillips[2] discuss the requirements for satisfactory stalling characteristics and Phillips[3] also discusses the consequences of poor stall characteristics and the influence of various design factors on the stalling characteristics. One type of stall-warning system which is capable of indicating more than one stage of warning is described by Bullivant,[4] another by Youngman,[5] and a summary of several

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[1] Gilruth, R. R., "Requirements for Satisfactory Flying Qualities of Airplanes." Washington: NACA Report 755, 1943, pp. 8-9.

U.S. Govt. Printing Office or Supt. of Documents

[2] Phillips, William H., "Appreciation and Prediction of Flying Qualities." Washington: NACA Report 927, 1949, p. 32.

[3] Ibid., pp. 32, 33.

[4] Bullivant, Kenneth W., "Theory of Operation of the Vane-Type Prestall Detector," Aeronautical Engineering Review, Vol. 11, Feb. 1952, pp. 44-45.

J.A.S.

[5] Youngman, R. T., "Development of a Pre-stall Detector for Aircraft, British Ministry of Supply, S&T Memo 6/52, July 1952, 3 pp.

types of stall-warning devices is described by Zalovcik.[6] Zalovcik[7] also discusses the merits of various types of indicators.

Some research on the question of the proper frequency for the best indication of stall warning obtained from a survey of the opinions of test pilots, who had used one type of control column shaker, is described by Bethwaite and Langley.[8] For the case of changing frequency or changing amplitude, or both, the pertinent question is not so much what frequency or amplitude may be best detected but what change in frequency or change in amplitude is necessary in order for the change to be detected. In other words, for this case it is not the frequency or amplitude per se which is sensed but rather the change in these quantities, if great enough. This point is discussed in the article on Weber's Law by Pringle-Pattison[9] and Psychophysics

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[6] Zalovcik, John A., "Summary of Stall Warning Devices." Washington: NACA TN 2676, May 1952, 15 pp.

[7] Ibid., p. 4.

[8] Bethwaite, C. F., and R. A. Langley, "Note on Research into Some Aspects of Stall Warning Devices," The College of Aeronautics, Cranfield, Report No. 72, April 1953, 7 pp.

[9] Pringle-Pattison, Andrew Seth, "Weber's Law," Encyclopaidia Britannica, 1951 edition, XXIII, pp. 469-470.

by Boring[10] in relation to various stimuli and is borne out by the test of this paper for frequency and amplitude stimuli. Furthermore, the literature on experimental psychology[11,12,13,14,15] shows that generally for equal subjective sensitivity the ratio of the change in stimulus to the basic value of the stimulus remains a constant (Weber's Law) in the middle of the sensible stimulus range. This relationship has been observed in the senses of sight (brightness), hearing (loudness and frequency), steady forces, body vibration and others. Sometimes part of the

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[10] Boring, Edwin Garrigues, "Psychophysics," Encyclopaedia Britannica, 1951 edition, XVIII, pp. 720-721.

[11] Pringle-Pattison, Andrew Seth, op. cit.

[12] Boring, Edwin Garrigues, op. cit.

[13] Handbook Staff, Tufts College: "Handbook of Human Engineering Data for Design Engineers." Tech. Rept. SDC 199-1-1 NavExos P-643 (Contract N6onr-199, T.O. 1), Tufts College Inst. for Appl. Exp. Psychology, Dec. 1, 1949 (as listed in bibliography with the exception of Pt. VI).

[14] Chapanis, Alphonse, Wendell R. Garner, and Clifford T. Morgan: Applied Experimental Psychology; Human Factors in Engineering Design, John Wiley & Sons, Inc., 1949, pp. 89, 199, 208, 209, 316, and 317.

[15] Rosenblith, Walter A., Kenneth N. Stevens, and the Staff of Bolt, Beranek, and Newman: "Handbook of Acoustic Noise Control - Volume II.- Noise and Man." WADC Tech. Rept. 52-204, U. S. Air Force, June 1953, Ch. 16.

sensible range is cut off as, for example, in the sense of sight where with increase in brightness, rod vision takes over where cone vision leaves off and at the extreme brightness where tests have probably been discontinued to avoid damage to the eye.

The tests originally devised for this investigation were set up for the purpose of determining the best ranges of frequency and amplitude of stick-shaker vibration for use as a lift-margin indicator. These tests at first revealed little until a review of the literature brought out the concept of Weber's law and its modern modifications and statistical tests were designed to determine the sensitivities at various frequencies and amplitudes. Once established, these sensitivities applied with insight derived from these concepts better explained the results of the original tests.

## CHAPTER III

## APPARATUS

For the simulator tests a shaker was desired in which the frequency and amplitude could be varied independently. The available shaker that most nearly fitted these requirements was a pneumatic device. The shaker consisted of a double-acting piston-cylinder combination equipped with a slide valve. The travel of the cylinder was cushioned at each end by means of springs or rubber buffers between the ends of the cylinder and the ends of the piston rod which extended through the ends of the cylinder. The shaker was attached to the control stick by one end of the piston rod (Figure 1).

The frequency of the shaker was varied by means of a relay arranged to oscillate the slide valve. The relay operated on intermittent current supplied through a rotary switch turned by an electric motor. The speed of the motor, and hence the frequency of the shaker, was varied by varying the voltage to the motor.

The amplitude of vibration of the stick was varied at a given frequency by varying the pressure of the air supplied to the shaker.

The amplitude and frequency-response characteristics of the stick and shaker combination are shown in Figure 2

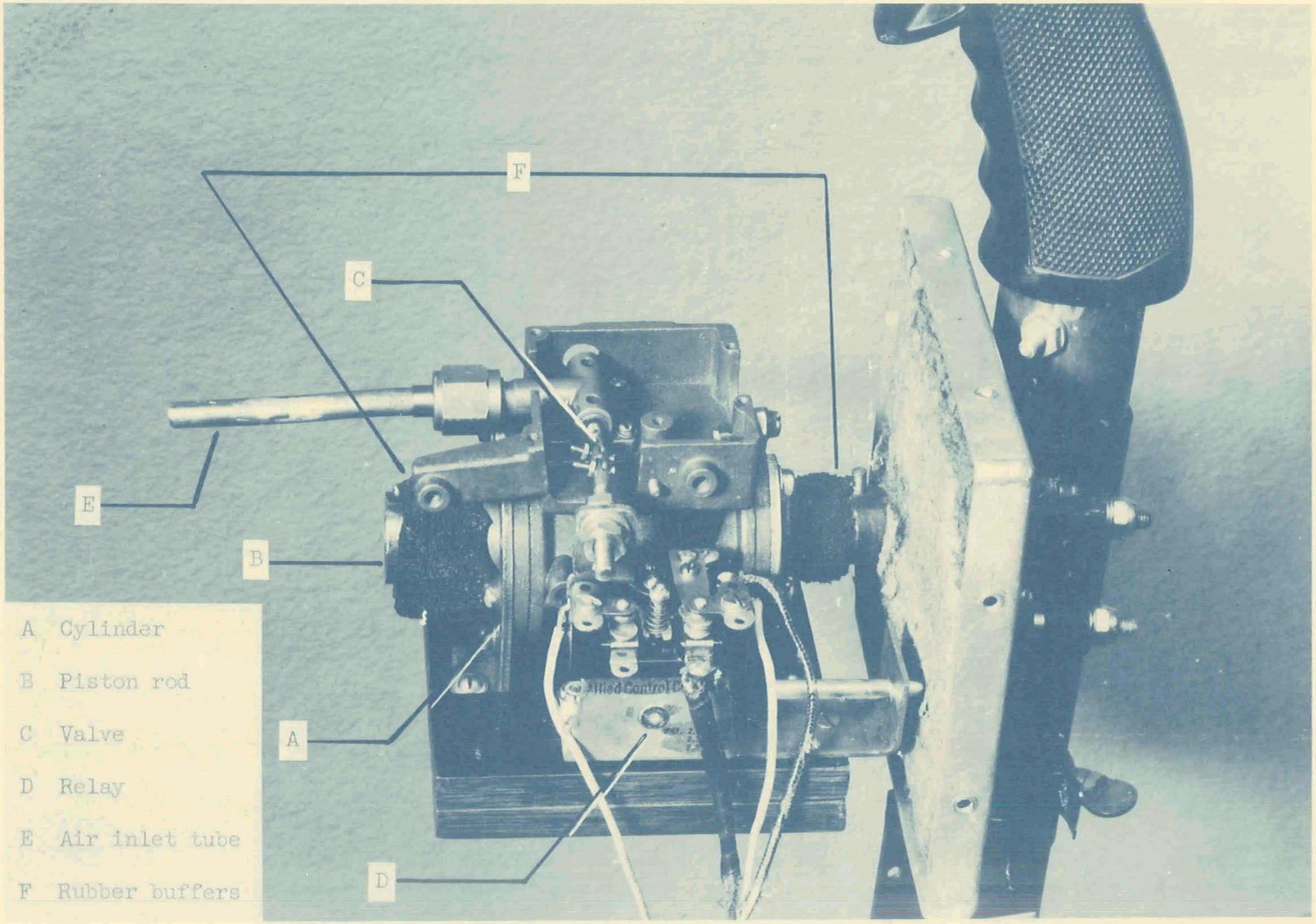


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FIGURE 1

PHOTOGRAPH OF STICK SHAKER

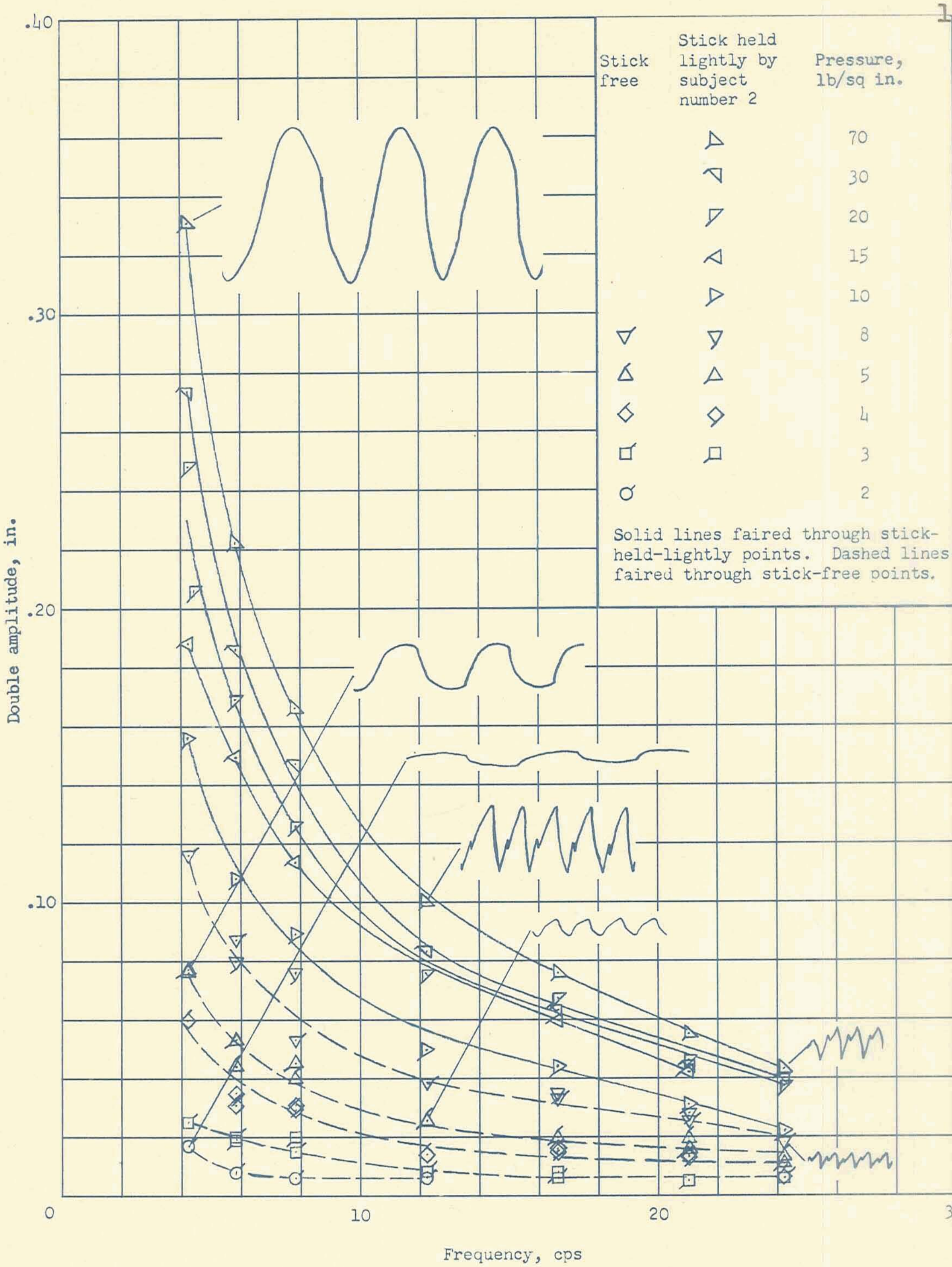



FIGURE 2

FREQUENCY-RESPONSE CALIBRATION OF STICK AND SHAKER COMBINATION FOR SHAKER WITH RUBBER BUFFERS. LINES FAIRING THE DATA POINTS ARE FOR CONSTANT PRESSURE. TYPICAL WAVE FORMS ARE SHOWN AT INDICATED POINTS for the shaker with rubber buffers between the ends of the cylinder and ends of the piston rod. Sample wave forms are also shown in Figure 2. The double amplitude of vibration was measured on the stick just above the shaker. The calibration was obtained by means of an optical apparatus which mainly consisted of a lens fixed to the stick just above the shaker, a light source fixed to the ground, and a film drum fixed to the ground which contained a strip of film moving perpendicular to the longitudinal direction in which the stick was shaking. The response characteristics are very similar with springs in place of the rubber buffers, except that the maximum amplitudes attained were somewhat smaller.

For the first phase of the simulator tests, a continuous variation of frequency and amplitude with variation in stick position was desired. However, because of mechanical complexities, a design permitting such a variation could not easily be obtained. A less complex mechanical and electrical arrangement permitted changes in stick position to produce discrete changes in motor voltage and air pressure and hence discrete changes in frequency and amplitude. This system was therefore adopted. The apparatus was constructed to allow disturbances simulating, for example, an angle-of-attack change in flight to be imposed on the system by making available to the operator of the equipment a disturbance-input control by which the frequency and amplitude of stick vibration could be changed from a given or reference frequency and amplitude independently of stick position.

A schematic diagram of the arrangement is shown in Figure 3. Four disturbance rates as determined by cam speed and cam shape were available to the operator. The range of the difference between stick displacement and disturbance-input-cam displacement, over which shaker operation was desired, was divided into 11 parts (steps), each of which closed a switch through a switching cam. Each switch was arranged to actuate some preset frequency and amplitude of the shaker through relays, resistances, and air-pressure valves (Figure 4). The displacement of the disturbance-input cam and the difference in displacements of the stick and the disturbance-input cam were measured in the tests by using NACA slide-wire control position transmitters.

The ideal functional characteristics of the apparatus for the first phase of the tests are illustrated by the block diagram in Figure 5. In addition to the vibrational frequency and amplitude signals from the shaker, the subject may have also gained clues from the noise of the stick shaker and the air valves, a light spring-force feedback to the stick, and the inertia of the cams. An attempt was made to

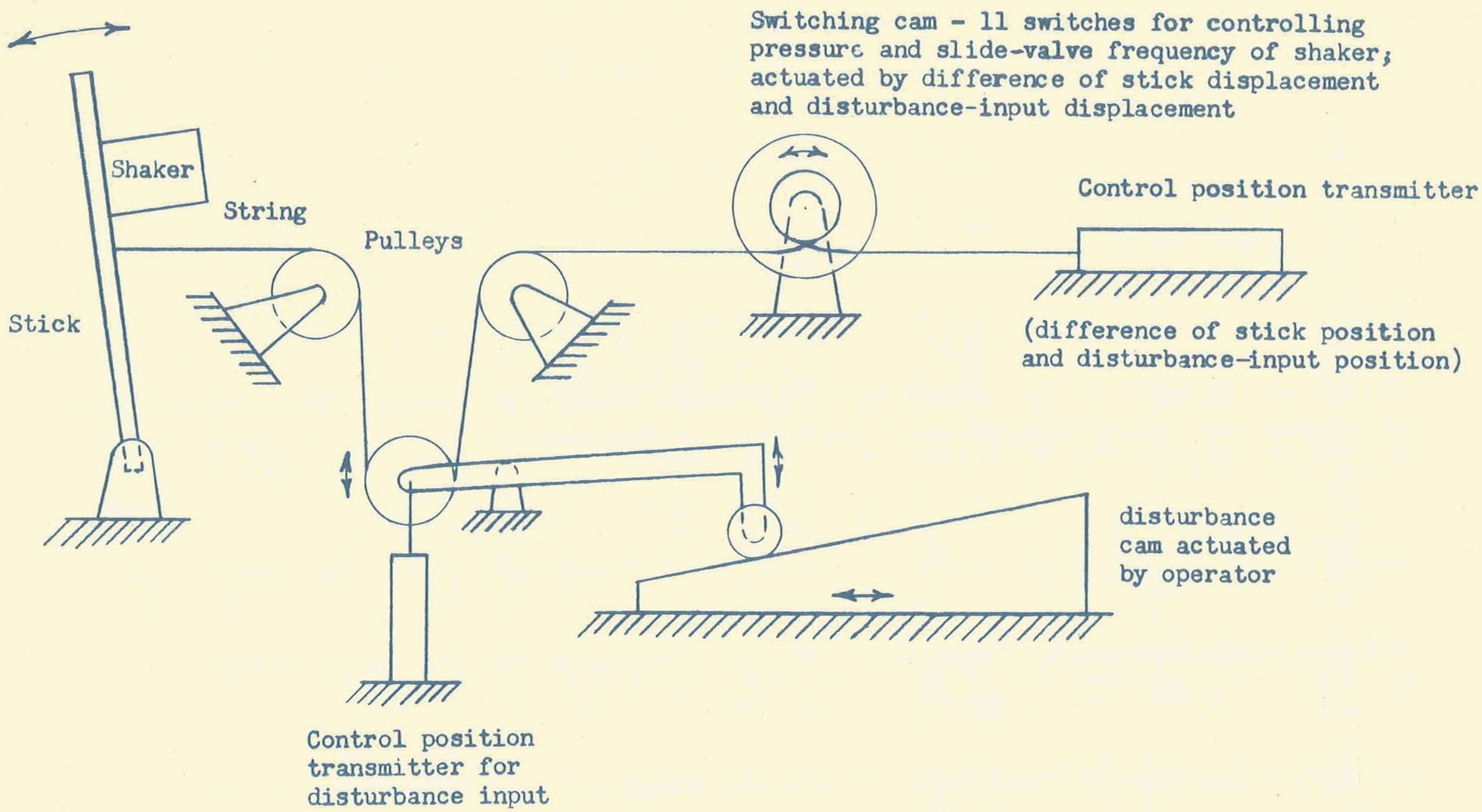
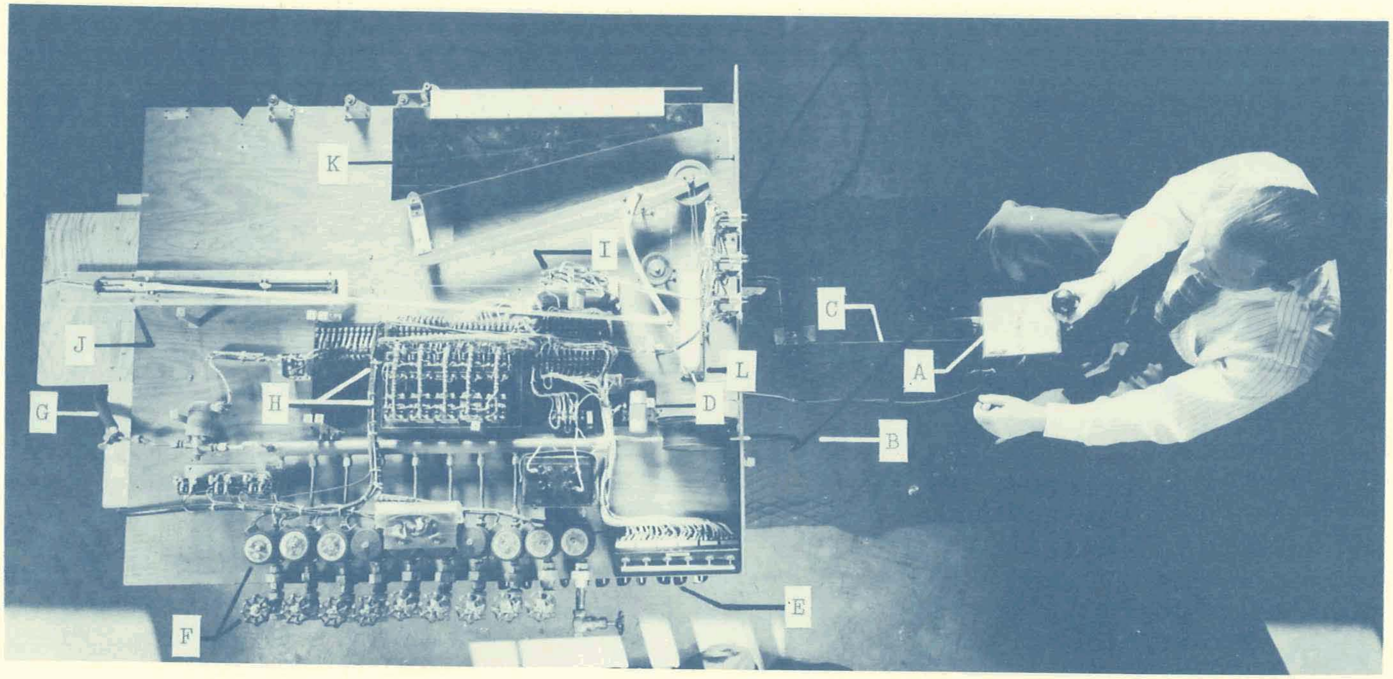



FIGURE 3

SCHEMATIC DIAGRAM OF THE ARRANGEMENT FOR IMPOSING AN ARBITRARY INPUT OF FREQUENCY AND AMPLITUDE OF STICK VIBRATION, FOR ALLOWING THE SUBJECT TO COMPENSATE FOR THE ARBITRARY INPUT, AND FOR MEASURING THE SUBJECT'S PERFORMANCE



A Box containing shaker

B Input air hose to shaker

C String from stick

D Motor controlling frequency

E Rheostats

F Valves controlling pressure to shaker

G Air supply hose

H Relays

I Output or switching cam

J Output control position transmitter

K Disturbance-input cam

L Disturbance-input control position transmitter

L-83216.1

FIGURE 4

PHOTOGRAPH OF STICK-SHAKER EQUIPMENT WITH SUBJECT READY FOR TEST

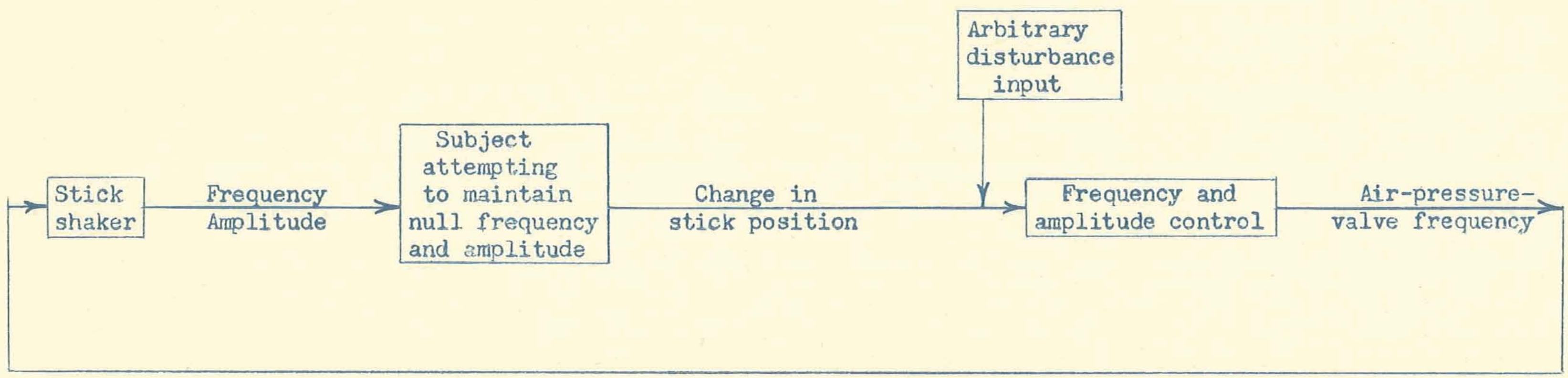



FIGURE 5

BLOCK DIAGRAM ILLUSTRATING THE IDEAL FUNCTIONAL CHARACTERISTICS OF THE APPARATUS IN TESTS TO DETERMINE ABILITY OF A SUBJECT TO MAINTAIN A SELECTED STICK-SHAKER FREQUENCY AND AMPLITUDE take out the spring-force feedback by an additional mechanical linkage and to mask the noise by playing back shaker noise previously recorded on tape.

For the second phase of the tests, it was desired to determine the minimum change in frequency or amplitude that a subject could detect. For this purpose, the frequency and amplitude step-control equipment of Figures 3, 4, and 5 was disconnected. The amplitude was varied by manual operation of an air-pressure valve and the frequency was varied by manual operation of rheostats controlling the voltage to the frequency-control motor.

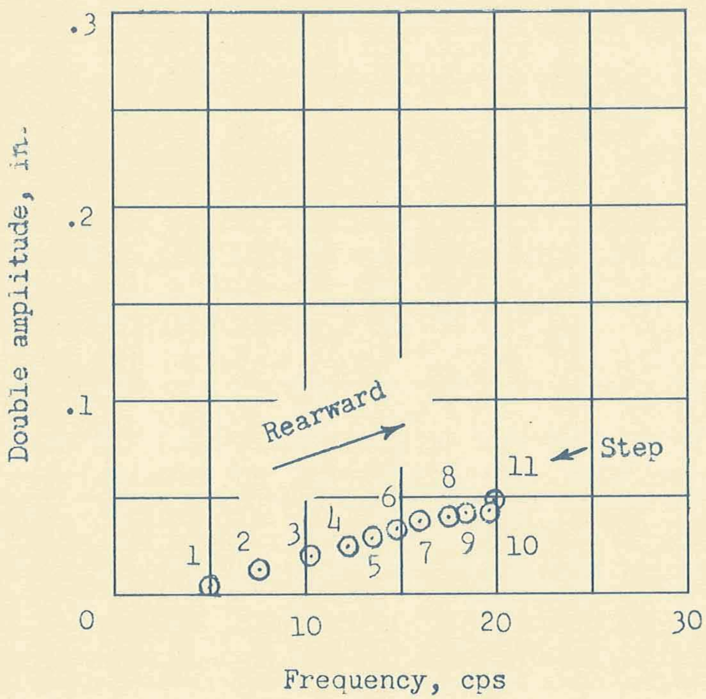
No provision was made for determining the effect of various steady stick forces on the ability of subjects to sense changes in vibration. When the stick was in a position near neutral, it could be balanced against the light force of the spring in the control position transmitter which measured the subject's output; otherwise it was overbalanced.

## CHAPTER IV

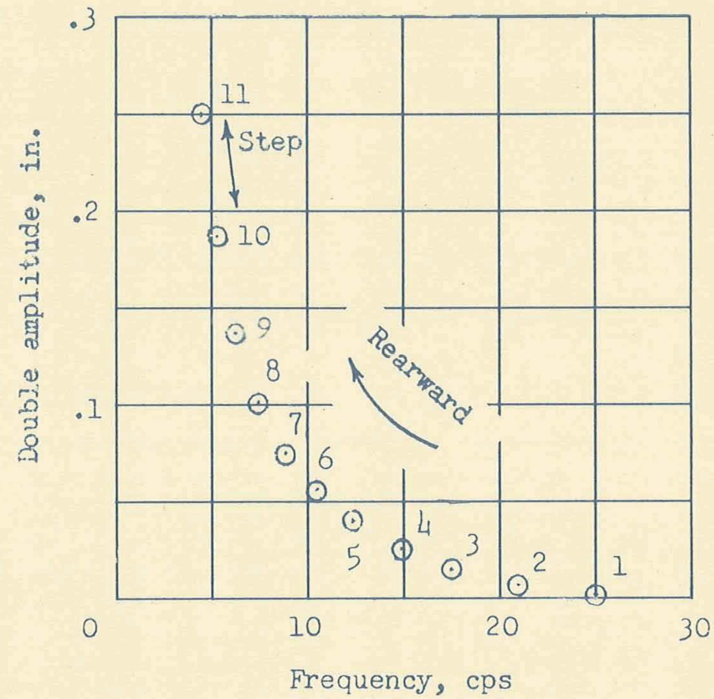
## PROCEDURE AND RESULTS

### Ability of Subject to Maintain a Selected Stick-Shaker Frequency and Amplitude

Description of tests.- Tests were made to determine how well a subject could maintain a selected stick-shaker frequency and amplitude when arbitrary disturbances in the form of amplitude and frequency changes were imposed on the system. Two of the representative variations of frequency and amplitude with stick displacement that were tried are shown in Figure 6. The variations of stick vibration tried were based on the premise that, in an actual application, the intensity of the vibration should start at zero at some angle of attack or lift coefficient well below the stall and increase to an uncomfortable level just before the stall to provide a warning. Variation in amplitude of vibration was therefore required, but it was believed that variation in frequency might be more accurately sensed in attempting to hold a given angle of attack. The arrangements tested, therefore, involved simultaneous variations of amplitude and frequency. Variation A, shown in Figure 6(a), consisted of increasing the amplitude and frequency in 11 steps with rearward stick displacement. The maximum amplitude that




(a) Increasing frequency and increasing amplitude with rearward stick displacement (variation A).




(b) Decreasing frequency and increasing amplitude with rearward stick displacement (variation B).

FIGURE 6

VARIATIONS OF FREQUENCY AND DOUBLE AMPLITUDE OF STICK-SHAKER VIBRATION WITH SWITCHING OR OUTPUT CAM DISPLACEMENT (IN STEP NUMBERS) USED IN TESTS TO DETERMINE ABILITY OF SUBJECT TO MAINTAIN A SELECTED STICK-SHAKER FREQUENCY AND AMPLITUDE could be attained with variation A was nominally 0.05 inch due to limitations of the equipment as evidenced in the frequency-response calibration (Figure 2). For variation B (Figure 6(b)) the amplitude increased while the frequency decreased in the 11 steps with rearward stick displacement. In variation B the ratio of the change in frequency from one step to the next to the frequency of the step was constant and the ratio of change in amplitude from one step to the next to the amplitude of the step was nearly constant. These constant amplitude and frequency ratios were made as large as possible for the ranges of amplitude and frequency obtainable with the equipment on the assumption that they would represent the maximum available equal stimuli between steps. (This equal-stimuli concept was based on Weber's law in psychology which states that the ratio of the change in stimulus to the total magnitude of the stimulus is a constant for the subject to just notice the change and for equal subjective perception or sensation of the change.[16,17])

The rate of imposing the disturbances ranged, for frequency, between 0.08 and 8 cycles per second per second and, for double amplitude, between 0 and 1.3 inches per second.

So what?

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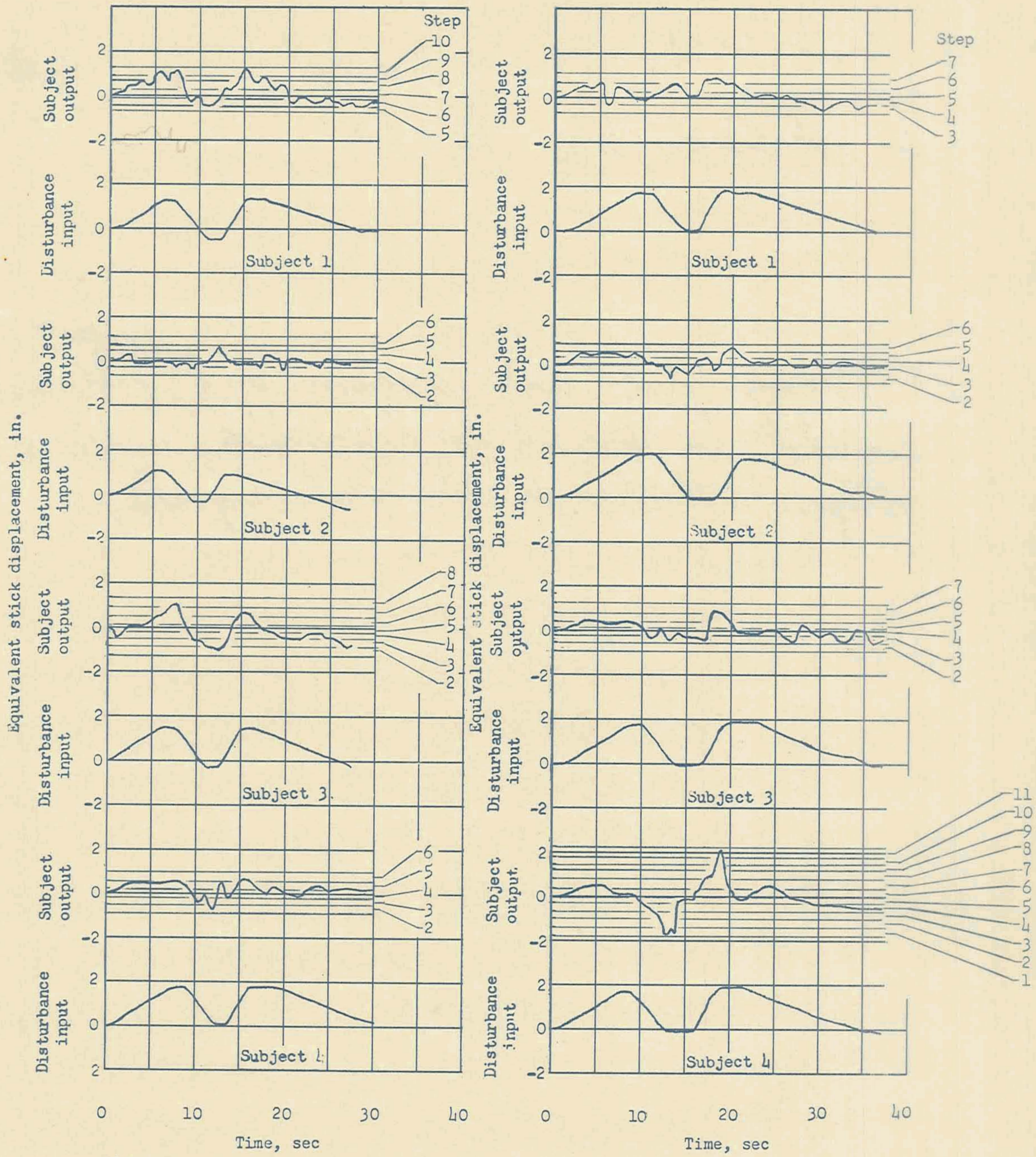
[16] Pringle-Pattison, Andrew Seth, *op. cit.*

[17] Boring, Edwin Garrigues, *op. cit.*

With variation A (Figure 6(a)) the subjects were instructed to select a step with an amplitude and frequency they thought they could most easily sense and then attempt to maintain, or null on that step. For this type of variation, the subjects were also given a training period of about 10 to 15 minutes per day for about 10 days prior to the day of the tests. For variation B (Figure 6(b)), the subjects were asked to try to null on step 4. However, there were no training periods preceding the day of the tests using variation B since the training periods used with variation A appeared to have little effect on the subject's performance, although this was not conclusively determined. In each of the series of tests a standard type of disturbance (Figure 7) was introduced after the subject spent 10 to 15 minutes familarizing himself with the variation of frequency and amplitude with stick displacement that was being used.

Results.- The results of the tests are shown in Figure 7 for several subjects in the form of time histories of the difference in displacements of the stick and disturbance-input cam (labeled "subject output") and time histories of the disturbance input, both expressed in inches of equivalent stick displacement. The corresponding steps are indicated as the spaces between the horizontal lines which represent the switching points between steps. A perfect compensation would be indicated in the figure by a




(a) Increasing frequency and increasing amplitude with rearward stick displacement (variation A).

(b) Decreasing frequency and increasing amplitude with rearward stick displacement (variation B).

FIGURE 7

TIME HISTORIES OF DISTURBANCE INPUT AND SUBJECT OUTPUT IN TERMS OF EQUIVALENT STICK DISPLACEMENT SHOWING ABILITY OF SUBJECT TO MAINTAIN A SELECTED STICK-SHAKER FREQUENCY AND AMPLITUDE curve contained within one step. A fixed stick, or no compensation during a disturbance input, would be indicated by an output curve identical to the disturbance-input curve. Since perfect compensation could not be expected from a subject unless signals other than frequency and amplitude changes were being received, the best performance that could be obtained would be a one-step variation from the desired null.

why not plot the differ.

Although more subjects (pilots and nonpilots) were tested with variation A than are indicated in Figure 7(a), the results are shown principally for comparison with the results in Figure 7(b) for the subjects who were available for both series of tests.

In Figure 7(a), subjects 1 and 3 had little success in compensating for the disturbance, whereas subjects 2 and 4 had better performance. It is noteworthy that (see Figure 6(a)) the percentage changes in frequency and amplitude at the null points picked by subjects 2 and 4 were greater than for those picked by subjects 1 and 3. This would seem to indicate a correlation between performance and percentage change in stimuli as would be expected from Weber's law. The results in Figure 7(b) (where all subjects nulled on step 4) indicate that, except where the most rapid changes occurred, the performance of all subjects was such that they permitted a change of only two steps from the null. The corresponding change in amplitude is about 120 per cent and the change in frequency is about 40 per cent (Figure 6(b)). It cannot be determined definitely whether the subjects were primarily sensing a change in amplitude or frequency or both (with variation B). For the conditions of variation A, however, the percentage amplitude variation was very much smaller than that for variation B; whereas the percentage frequency change was of similar magnitude. The subjects were therefore apparently using frequency as the primary reference with variation A and possibly also with variation B.

An important factor in the use of stick vibration as an indicator would be the ability to remember the feel of the vibration condition corresponding to a desired flight condition over a period of time sufficient to complete, for example, the final approach to landing, since no fixed reference is available as in a visual indicator. This factor was not investigated except to the extent of the time covered by the tests shown in Figure 7(b), or about 35 seconds. Note that, in all cases in Figure 7(b), at the end of the test the subjects had restored conditions to within one or two steps of the initial conditions or within 60 to 120 per cent in amplitude and 20 to 40 per cent in frequency.

From the foregoing results, stick vibration varying with angle of attack or lift coefficient appears to be usable as an indicator for maintaining a given flight condition, at least for a limited period of time, provided that the allowable variation from the desired flight condition, say 1° in angle of attack, produces either a change in amplitude of vibration of 60 to 120 per cent or a variation in frequency of 20 to 40 per cent, or both. It should be pointed out that sensing the feel of the stick vibration corresponding to a desired flight condition would probably require initially finding this flight condition by reference to some other indicator such as a visual dial indicator. Furthermore, vibrations transmitted to the stick from the airplane or the controls could have a detrimental effect on the ability of pilots to sense changes in vibrations from the stick shaker; however, this factor was not investigated.

Although a masking noise was used in the tests in an attempt to nullify any signal that a subject could be receiving from shaker and control-equipment noise, the effect of shaker and control noise and masking noise on the subject's performance was not conclusively determined. Some tests made with the masking noise turned off indicated no noticeable change in subject performance. A few tests were also made with the shaker and control equipment inoperative but with a slight force feedback due to the inertia of the switching cam and springs of the control-position transmitters present during the disturbance input. All subjects tested except one found sensing this force feedback as difficult as sensing vibrations, particularly in that no indication of the original null was available to the subject. One subject, however, was able to do better with inertia feedback than anyone was able to do with vibrations (results not shown). Nevertheless, the lack of a null indication over a long period of time was detrimental to his performance also.

## Ability of Subject to Detect Changes in Frequency or Amplitude

Description of tests.- In the tests to determine the ability of a subject to detect changes in amplitude, the shaker was first set into operation at some predetermined frequency and amplitude and the air pressure was noted. After the subject held the stick for a few seconds or long enough to establish a feel of the level of vibration, the amplitude was increased or decreased more or less continuously at random rates by the operator through manual operation of the air-pressure valve. When the subject realized that the amplitude had changed, he signaled to the operator, who then discontinued the pressure change. The change in pressure from the original pressure was observed by the operator. Actually, the observed pressure change, and hence the indicated amplitude change, was probably somewhat greater than the value which the subject first felt because of the lag in the response of the subject and the operator and the finite rate of change of pressure.

In the tests to determine the sensitivity of the subject to frequency change, the procedure was very similar. The shaker was first set into operation at a predetermined amplitude and frequency. The frequency was then changed by manually adjusting a rheostat which controlled the voltage of the frequency-control motor while the air pressure was kept constant. In similarity to the case of changing amplitude the observed value of frequency change was probably somewhat greater than that first noticed by the subject because of lag in operator and subject response and the finite rate of change of frequency. Because of the response characteristics of the stick and shaker combination (Figure 2), the amplitude did not remain constant but changed somewhat with change in frequency at a given pressure. As can be seen in Figure 2, the change in amplitude with change in frequency is greater at the higher pressures and the lower frequencies for this particular shaker and stick combination.

For amplitude sensitivity, two tests were made at a frequency of 26 cycles per second and basic amplitudes of 0.014 inch and 0.032 inch and one test at a frequency of 10 cycles per second and a basic amplitude of 0.032 inch. For frequency sensitivity two tests were made with a basic frequency of 18.8 cycles per second and amplitudes of 0.013 and 0.066 inch (4 lb/sq in. and 70 lb/sq in.). There were 2 to 4 subjects for each test with 44 to 91 trials for each subject.

Results.- The results of the amplitude-sensitivity tests are presented in Figure 8 as frequency distributions of the ratio of the change in amplitude detected to the basic amplitude $\left(\frac{\Delta A}{A}\right)$. The results of the frequency-sensitivity tests are presented in Figure 9 as frequency distributions of the ratio of the change in shaker frequency detected to the basic shaker frequency $\left(\frac{\Delta f}{f}\right)$.

The results indicate that, over the limited conditions covered in the tests, the amplitude sensitivity at a given frequency increased $\left(\text{lower mean value of } \frac{\Delta A}{A}\right)$ with increase in basic amplitude and also increased for a given basic amplitude with increase in shaker frequency. Obviously, Weber's law, which would imply a constant value for the amplitude-change ratio at a constant frequency, does not apply to amplitude sensitivity over the conditions covered

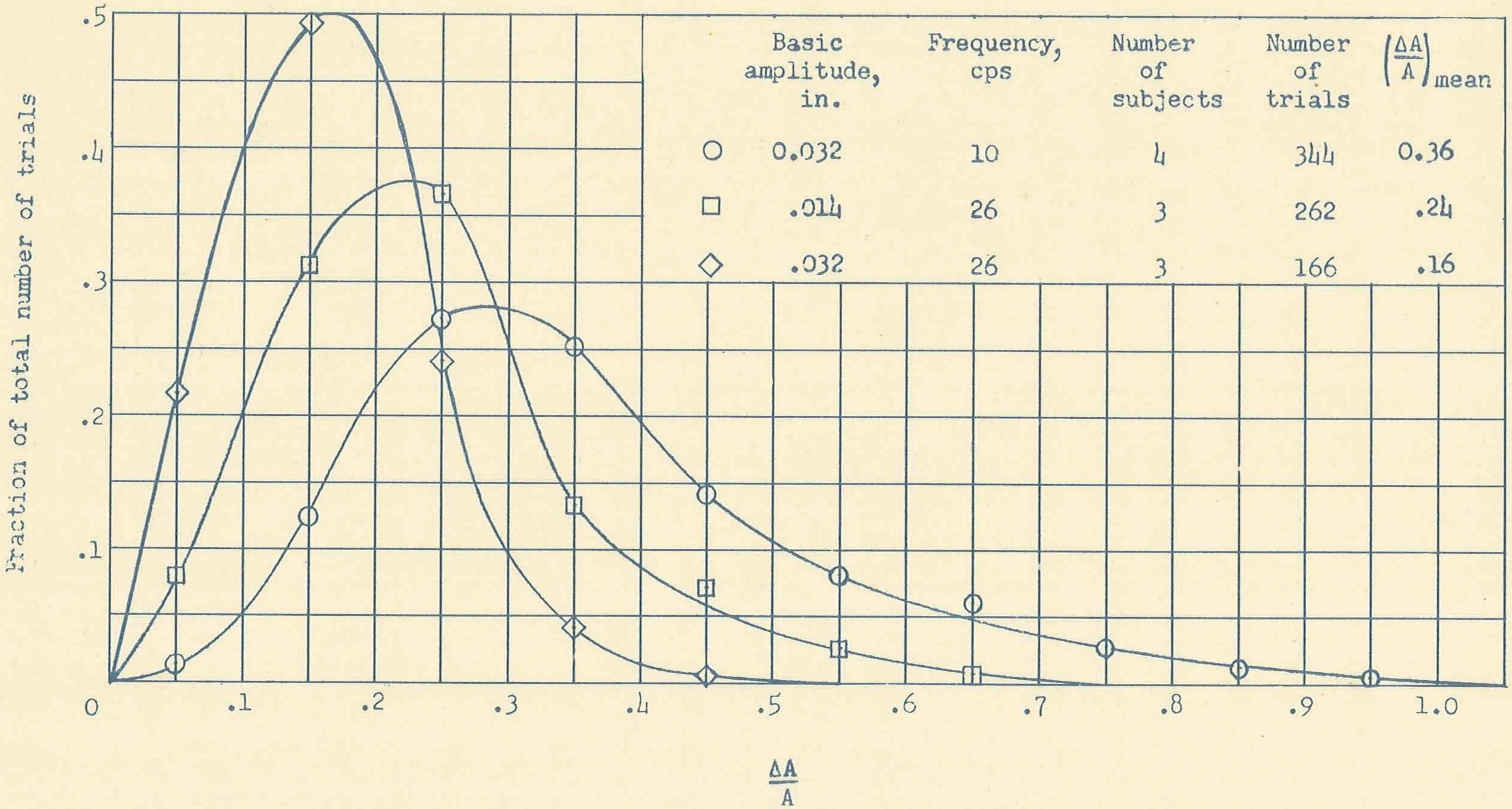



FIGURE 8

FREQUENCY DISTRIBUTION OF THE RATIO OF CHANGE IN AMPLITUDE OF STICK VIBRATION DETECTED TO THE BASIC AMPLITUDE

| | Basic frequency, cps | Constant pressure, lb/sq in. | Approximate constant amplitude, in. | Number of subjects | Number of trials | $\left(\frac{\Delta f}{f}\right)_{mean}$ |
|---|---|---|---|---|---|---|
| ○ | 18.8 | 4 | 0.013 | 4 | 320 | 0.125 |
| □ | 18.8 | 70 | .066 | 2 | 169 | .125 |

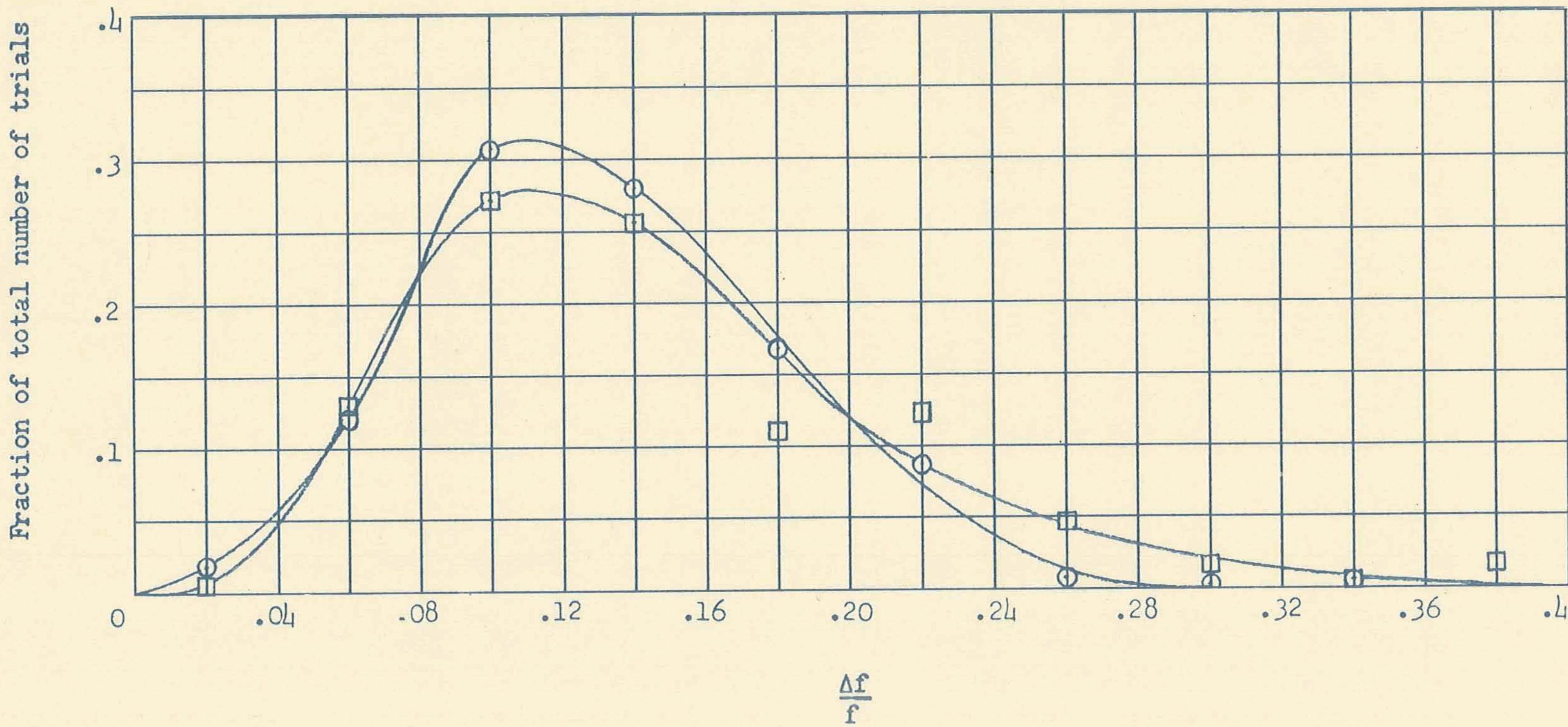



FIGURE 9

FREQUENCY DISTRIBUTION OF THE RATIO OF CHANGE IN FREQUENCY OF STICK VIBRATION DETECTED TO THE BASIC FREQUENCY in these tests. This increase in amplitude sensitivity with increase in amplitude and frequency indicates that the amplitudes and frequencies used in the tests are in the lower stimulus range.[18,19,20,21]

The results in Figure 9 indicate about the same frequency sensitivity at two different amplitudes. Comparison of the results in Figure 9 with those in Figure 8 indicates that, for the conditions covered, the subjects were more sensitive to frequency changes than to amplitude changes.

Since no tests were made for frequency sensitivity at more than one base frequency the relative position of the base frequency used with respect to the boundaries of the sensible stimulus range was not determined. However, similarity of the percentage change in frequency required to insure detection in 100 per cent of the trials (40 per cent) to the percentage change in frequency required to null for all but the fastest time rates of change of

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[18] Handbook Staff, Tufts College, op. cit.

[19] Chapanis, Alphonse, Wendell R. Garner, and Clifford T. Morgan, op. cit.

[20] Rosenblith, Walter A., Kenneth N. Stevens, and the Staff of Bolt, Beranek, and Newman, op. cit.

[21] McFarland, Ross A., Human Factors in Air Transport Design. McGraw-Hill Book Co., Inc., 1946, 670 pp.

frequency as shown in Figure 7 (also 40 per cent) over a base frequency range varying from 18.8 cycles per second (Figure 9) to 15 cycles per second (Figure 7(b)) and 10 cycles per second (Figure 7(a)) subjects 2 and 4) where an average total frequency change required remained roughly 40 per cent gives a rough indication that this is near the middle of the sensible stimulus range for frequency, where Weber's law may be applicable.

The results in Figures 8 and 9 indicate that, in order to insure sensing a change in stick vibration characteristics, up to 100-per cent change in amplitude or up to 40-per cent change in frequency may be required (changes detected in 100 per cent of trials). These values correspond approximately to the changes in stick-vibration frequencies and amplitudes that the subjects were generally able to detect and correct for, as shown in Figure 7.

## CHAPTER V

## RECOMMENDATIONS FOR FURTHER RESEARCH

The preliminary results have indicated many areas where further research would be desirable. Those discussed first are mainly concerned with effects not defined completely by this investigation; the others are concerned with extending the research to the limits of the human sensory ability and to the limits as governed by conditions probably existing in aircraft.

Among the variables not specifically separated from the main variables of the tests were the effects on the subjects ability to detect changes in frequency and amplitude of time rate of change of frequency, time rate of change of amplitude, and steady stick forces. Also not determined was the ability of a subject to maintain a given null point over a protracted period of time. Further tests to establish these effects would be in the nature of refinements and are not recommended solely for this purpose. Should further tests be made for other reasons, then it is recommended that these effects be investigated, if convenient.

The ability of a subject to detect changes in frequency at more than one basic frequency was not determined directly but was inferred to be approximately constant from the tests of the subjects ability to maintain a null at such frequencies. The direct determination would, of course, be more desirable. The sensitivities to changes in frequency and amplitude were established by these tests only at isolated basic frequencies and amplitudes in the range over which stick shakers have been used. Further research which would establish these sensitivities over the entire sensible range of frequency and amplitude is recommended.

The limits of the basic frequencies and amplitudes beyond which no changes in frequency and amplitude can be detected need to be established also. However, limits determined by laboratory ground simulators would probably not be the same as those actually existing in an aircraft. Therefore, a rough estimate of the limits based on an estimate of the actual conditions may be useful. The limits are estimated to range within the boundaries of the cross-hatched area of Figure 10. Also shown in Figure 10 are symbols and outlines representing the present tests.

The maximum amplitude of stick vibration may be limited to that which would deny the pilot a firm grip on the stick, which would interfere with his sensation of normal stick motions and forces, which would put dangerous stresses on the control system or which would cause dangerous motions of the airplane itself. The maximum

○ Amplitude varying
□ Frequency varying
} From tests of subjects ability to detect changes in frequency and amplitude (arrows show range of $\left(\frac{\Delta A}{A}\right)_{mean}$ and $\left(\frac{\Delta f}{f}\right)_{mean}$)

◇ Variation A
▽ Variation B
} From tests of subjects ability to null on a given frequency or amplitude

◸ Variation C

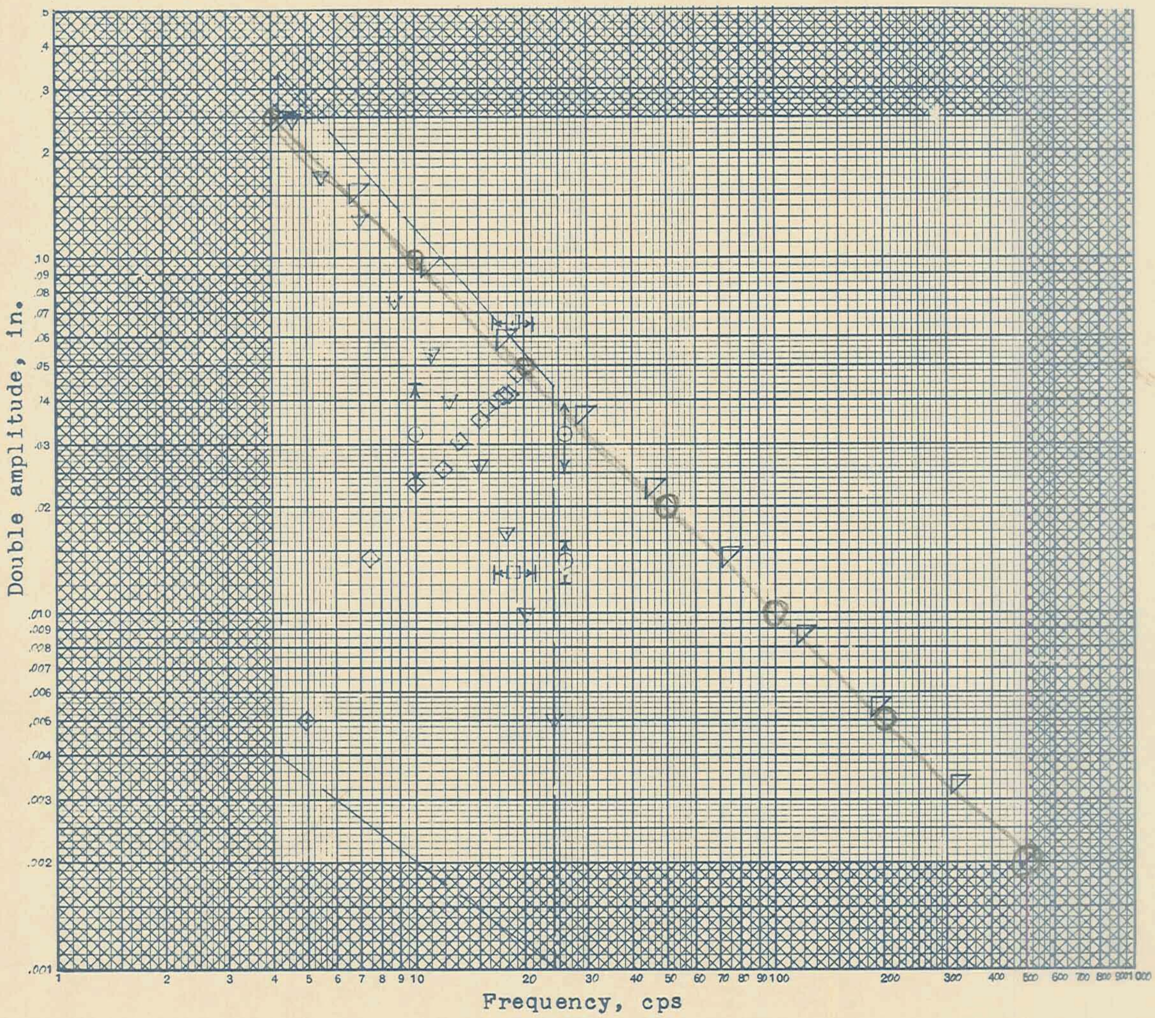


FIGURE 10

LIMITS OF STICK-SHAKER VIBRATION ESTIMATED USABLE IN AIRCRAFT (CROSS-HATCHED AREA). ALSO SHOWN ARE SYMBOLS AND OUTLINES (DASHED LINES) REPRESENTING THE PRESENT TESTS AND VARIATION C SUGGESTED FOR USE IN AIRCRAFT IF RESOLUTION EQUIVALENT TO 11 STAGES WAS REQUIRED double amplitude limits used in Figure 10 were obtained from pilots' opinions which ranged between 1/4 inch to 1/2 inch.

The minimum amplitude of stick-shaker vibration may be limited to that which would not be masked by airplane or control-stick vibration from sources other than the shaker, or which are just above the human sensory threshold for vibration through the hand. The limits shown in Figure 10 for the minimum double amplitude of vibration were estimated as from 0.001 inch to 0.002 inch. McFarland[22] describes studies in which vibrations existing in aircraft without serious vibration problems were of the order of 0.002 inch. It is believed that amplitude of vibration in jet aircraft will be less than 0.002 inch in the frequency range of interest here. McFarland[23] also discusses studies of the human sensory threshold to vibration (at the fingertip) which are of the order of 0.001 inch.

The minimum frequency limit of stick vibration may be that which would be confused with stick motions associated with airplane motions or control motions resulting from normal flight maneuvers; or that which would correspond approximately to the human reaction time period. Abrupt

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[22] McFarland, Ross A., op cit.

[23] Ibid., pp. 322-323.

flight maneuvers (pull-ups) have contained frequency components of as high as 1 cycle per second and the human reaction time period is of the order of 1/4 of a second.[24,25,26] If the stick shaker was vibrating at about the same frequency as a frequency component of the maneuver and both were approximately the frequency corresponding to the human reaction time, an out of phase relationship might exist between stick-shaker force and the stick-control force resulting in a control instability. Therefore, this area of frequency is avoided. Also McFarland[27] (after Geldard) indicates an increase in the threshold amplitude at the lower frequencies, suggesting perhaps the decrease in sensitivity in this frequency range to be expected near the lower limit of the sensible stimulus range.

The maximum frequency may be limited by that corresponding to the refractory period of the nerve fiber impulse.

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[24] Ibid., pp. 327-331.

[25] Handbook Staff, Tufts College, op. cit.

[26] Alphonse Chapanis, Wendell R. Garner, and Clifford T. Morgan, op. cit., pp. 280-281.

[27] McFarland, Ross A., op. cit., pp. 322-323, citing F. A. Geldard "The Perception of Mechanical Vibration." J. Gen. Psychol., Vol. 22, 243-308, April 1940.

According to Katz, "If the second stimulus comes within one or two thousandths of a second after the first, our nerve fiber does not respond; it must have a little rest pause after one impulse to be able to conduct the next."[28] Thus the maximum frequency beyond which no tactile stimulus may be sensed was taken to be between 500 and 1000 cycles per second. This may not be strictly applicable, since a nerve cable is composed of many fibers and a signal sent through one fiber in a given cycle may be sent through another fiber in the next cycle. Some support for these approximate maximum frequencies may be gained from an examination of the data shown by McFarland[29] (after Geldard) in which the threshold amplitude increases abruptly in this frequency range suggesting loss of sensitivity near these frequencies.

From Figure 10 it appears that the greatest area for further research is in the higher frequencies.

Defining the limits of the working area of basic frequency and amplitude provides a rough yardstick for the usefulness of the absolute values of the sensitivities obtained. In other words if $\frac{\Delta f}{f}$ and $\frac{\Delta A}{A}$ were constant, the maximum resolution that could be provided within the

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[28] Katz, Bernhard, "The Nerve Impulse," <u>Scientific American</u>, Vol. 187, p. 58, Nov. 1952.

[29] McFarland, Ross A., <u>loc</u>. <u>cit</u>.

inner limits of Figure 10 would be 15 steps or stages of the range of lift coefficient or angle of attack over which the shaker would operate for $\frac{\Delta f}{f} = 0.41$, and 8 stages for $\frac{\Delta A}{A} = 1.0$. (See Appendix for explanation as to how these numbers were obtained.) In application as a lift-margin indicator, the number of stages would be specified by the range of lift coefficients over which the shaker would operate and the accuracy in lift coefficient desired within this range; ~~the change from one stage to the other corresponding to the accuracy required in lift coefficient~~. If 11 stages for both frequency and amplitude were required as in Variations A and B, then assuming $\frac{\Delta f}{f}$ and $\frac{\Delta A}{A}$ constant for the inner limits of Figure 10 $\frac{\Delta f}{f} = 0.62$ and $\frac{\Delta A}{A} = 0.62$. (See Appendix for explanation as to how these numbers were obtained.) This variation is shown in Figure 10 as Variation C where the symbols represent each stage. The frequency ratio for 11 stages $\left(\frac{\Delta f}{f} = 0.62\right)$ would be higher than $\frac{\Delta f}{f}$ detected in 100 per cent of the trials of Figure 9, while the amplitude ratio $\left(\frac{\Delta A}{A} = 0.62\right)$ would be equal to or higher than $\frac{\Delta A}{A}$ detected in 90 per cent of the trials of Figure 8. (It may be noted that variation C is approximately amplitude $= \frac{1}{\text{frequency}}$ as shown in figure 10.

## CHAPTER VI

## CONCLUDING REMARKS

An exploratory investigation with laboratory apparatus was made to determine whether a pilot could use stick vibration varying in either frequency or amplitude, or both, with angle of attack or lift as an indicator for maintaining a desired margin of angle of attack or lift below the stall. The results of the test indicate that, once established, a given flight condition can probably be maintained by sensing variations in stick vibration at least over the period of time covered by the tests (35 seconds), provided that allowable variations from the desired flight condition produce either changes in amplitude of vibration of about 100 per cent or changes in frequency of about 40 per cent, or (preferably (?)) both. In the ranges of amplitude and frequency covered in the tests, sensitivity to amplitude changes increased with increase in amplitude and frequency; sensitivity to frequency changes did not appear to be materially affected by amplitude or frequency. No tests were made of the effects of extraneous vibrations from other sources on the ability to sense the vibrations produced by the stick shaker.

It is recommended that a more thorough investigation be made of the limits of human sensitivity to vibration through the hand and of the sensitivities within these limits. Estimates were made of the frequency and amplitude limits of stick-shaker vibration as may exist in an actual installation in an aircraft. A variation of frequency with amplitude within the estimated limits is suggested, which it is calculated would have high enough sensitivity to provide a resolution equivalent to 11 stages of the range of lift coefficient or angle of attack over which such a stick shaker would operate.

approx $f \propto \frac{1}{A}$

Spell out more clearly —
which do you advise —
a) frequency
b) amplitude
c) a combination and if so, what kind of combination

Would advise a combination, the kind of combination depending on whether ~~a fixed~~ the requirements are a fixed number of stages or the maximum resolution. If the requirements are a fixed number of stages less than the maximum I would suggest an equal number of stages of frequency and amplitude using variation C. If the requirement is ~~the~~ maximum sensitivity I would suggest 15 stages of frequency and 80 [illegible] amplitude also using variation C.

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APPENDIX

APPENDIX

Based on the assumption that $\frac{\Delta f}{f}$ = constant, the relation between the frequency ratio, $\frac{\Delta f}{f}$, the maximum basic frequency, $f_n$, the minimum basic frequency, $f_1$, and the number of steps or stages, $n_f$, can be derived as follows:

$$\frac{\Delta f}{f_1} = \frac{f_2 - f_1}{f_1} = \text{constant, } K$$

so

$$\frac{f_2}{f_1} = \frac{\Delta f}{f_1} + 1 = K + 1$$

and similarly

$$\frac{f_3}{f_2} = \frac{\Delta f}{f_2} + 1 = K + 1$$

and so on to

$$\frac{f_n}{f_{n-1}} = \frac{\Delta f}{f_{n-1}} + 1 = K + 1$$

thus

$$\frac{f_n}{f_1} = \frac{f_n}{f_{n-1}} \times \frac{f_{n-1}}{f_{n-2}} \times \frac{f_{n-2}}{f_{n-3}} \times \ldots \times \frac{f_3}{f_2} \times \frac{f_3}{f_1}$$

therefore

$$\frac{f_n}{f_1} = (K + 1)^{n_f - 1}$$

and

$$\frac{\Delta f}{f} = K = \left(\frac{f_n}{f_1}\right)^{\frac{1}{n_f - 1}} - 1$$

If the number of steps, $n_f$, is desired, it can be obtained from the above relation as:

$$n_f = \frac{\log_e\left(\frac{f_n}{f_1}\right)}{\log_e\left(\frac{\Delta f}{f} + 1\right)} + 1$$

The derivations of the equations $\frac{\Delta A}{A} = \left(\frac{A_n}{A_1}\right)^{\frac{1}{n_A - 1}} - 1$ and $n_A = \frac{\log_e\left(\frac{A_n}{A_1}\right)}{\log_e\left(\frac{\Delta f}{f} + 1\right)} + 1$ are exactly analogous since they are of the same form.

The number of steps, $n_f$ and $n_A$, mentioned on page 39 were obtained using $f_n = 500$ cps, $f_1 = 4$ cps, $\frac{\Delta f}{f} = 0.41$, $A_n = 0.25$ inch, $A_1 = 0.002$ inch, and $\frac{\Delta A}{A} = 1.0$, resulting in $n_f = 15$ and $n_A = 8$.

The frequency ratio, $\frac{\Delta f}{f}$, and amplitude ratio, $\frac{\Delta A}{A}$, mentioned on page 39 were obtained using $n_f$ and $n_A = 11$, $f_n = 500$ cps, $f_1 = 4$ cps, $A_n = 0.25$ inch, and $A_1 = 0.002$ inch, resulting in $\frac{\Delta f}{f} = 0.62$ and $\frac{\Delta A}{A} = 0.62$.